Attachment 3

NAG3-87

# STRUCTURAL DYNAMICS ANALYSIS TOOLS FOR DESIGN OF LARGE WIND TURBINES

STATE-OF-THE-ART REVIEW

Prepared for the
Wind Energy Project Office
NASA Lewis Research Center
Cleveland, Ohio 44135

REVIEWERS:

Robert W. Thresher
Oregon State University
Corvallis, Oregon 97331

John Dugundji
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Kurt H. Hohenemser
Washington University Technology Associates
St. Louis, Missouri 63144

William C. Walton, Jr.
NASA Langley Research Institute
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September 1981

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## FOREWORD

On February 10, 1981, four independent reviewers were asked by Ronald L. Thomas, Manager of the Wind Energy Project Office at the NASA Lewis Research Center, to attend the Second DOE/NASA Workshop on Wind Turbine Dynamics (Feb. 24-26, 1981 in Cleveland) and to assess the analysis tools available for predicting the structural dynamic behavior of large wind turbines. The reviewers were selected on the basis of their experience and authority in the fields of structural and rotor dynamics. This report contains their review comments, with a summary by Professor Robert W. Thresher of Oregon State University.

The Wind Energy Project Office expresses its appreciation to these expert reviewers for their care and insight in the preparation of the following reports. Every effort will be made to improve the quality and scope of structural dynamics analysis methods employed in the design of large wind turbines, in accordance with reviewers' recommendations.

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Summary of Reviewers Comments

from

The Review of Structural Dynamics Analysis Tools for
Design of Large Wind Turbines

by

R.W. Thresher
Mechanical Engineering Department
Oregon State University

April 29, 1981

## Introduction

The Wind Energy Project Office at NASA Lewis Research Center, requested four independent reviewers to make comments on the working level of structural analysis methods for the design of large wind turbine systems. The reviewers selected were:

Professor John Dugundji
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
Cambridge, MA

Dr. K.H. Hohenemser
2421 Remington Lane
St. Louis, MO

Professor R.W. Thresher
Mechanical Engineering Department
Oregon State University
Corvallis, OR

Mr. W.C. Walton, Jr.
NASA-Langley Research Center
Hampton, VA

In a memo to the reviewers, Mr. Ronald Thomas, Manager of the Wind Energy Project Office, set forth the following three questions to focus the scope of the four reviews:

1. Is the current working level of analytical methods satisfactory to support the design of the next generation of large wind turbines?

2. Is the large wind turbine community making use of available analytical tools?

3. Are there other areas of concern in the entire field of wind turbine structural dynamics, including analysis, design, and testing?

## Summary of Review Results

In order to summarize these reviews, I would like to present the responses to these specific questions in as short a form as possible.

Question #1 - Is the current working level of analytical methods satisfactory to support the design of the next generation of large wind turbines?

Responses:

J. Dugundji "In aerodynamics, for HAWT's, the state-of-the-art tools seem satisfactory for performance analyses, but not for dynamic loads and unsteady effects. In structural dynamics, for HAWT's, the state-of-the-art tools seem satisfactory again for steady-state performance analyses, but not for transient and dynamic loads. In acoustics, the state-of-the-art seems to be emerging satisfactorily."

K. Hohenemser "The application of available analytical methods cannot guarantee a correct prediction of structural dynamics properties of wind turbines. Many of the methods are too complex for aplication to dynamic design anyway. The aerodynamic inputs are crude and oversimplified."

R. Thresher "The dynamic analysis codes have good predictive capability for the less flexible turbine designs, but I do not feel that they are satisfactory to support the design of a generation of highly flexible wind turbines. The computer codes have not been validated for the soft systems."

W. Walton "Structural dynamics analysis tools are adequate to support designs of the next large wind turbines."

Question #2 - Is the large wind turbine community making use of available analytical tools?

Responses:

J. Dugundji — No direct response was made to this question, but it was clear that this reviewer feels the tools are being used satisfactorily.

K. Hohenemser — No direct response was made to this question, although the text implies that the available tools are in use.

R. Thresher — "It is my opinion that the large wind turbine technical community is making use of the available codes, generally their own. However, most of the design teams are not confident of their codes for the new flexible turbines, although few would openly admit it."

W. Walton — "The tools are being satisfactorily utilized."

Question #3 - Are there other areas of concern in the entire field of wind turbine structural dynamics, including analysis, design, and testing?

Responses:

J. Dugundji — Excerpts from the Personal Impressions Section.

"The wind turbine field is moving ahead steadily, the body of knowledge is growing, and there is excitement as analysis, actual hardware, and operational experience develops.

Newer and more bold concepts are being tried, such as upwind rotors, free yaw machines, teetering blades, partial span controls, softer mounts, VAWT concepts, etc. More efficient wind turbines seem to be evolving from these concepts.

Wind Turbine power performance predictions are sensitive to good estimates of drag coefficient $C_D$.

The "vortex-ring state" at high tip speed ratios should be better defined and recognized.

VAWT aerodynamics and structural dynamics seem more difficult than for HAWT's. This is partly due to the fact that unlike HAWT's, the VAWT's have no comparable established helicopter theory to draw from.

More accurate knowledge of aerodynamics requires investigation of vortex theories for both HAWT's and VAWT's.

For HAWT's, the free yaw behavior should be investigated further. The effects of coning angle, wind gusts, and yaw gusts should be better defined.

Knowledge of atmospheric turbulence is being gathered and applied to determine the power quality and fatigue response of the rotors. These involve random stochastic processes. Also required is a good discrete gust load criterion, based on statistical experience, comparable to the 1-cos gust used in the design of aircraft. Survival at hurricane wind loads seem to be reasonably defined.

Effects of transient loads such as gusts, emergency shut-downs, braking, on-off operation, etc., are still difficult to predict because of importance of damping, nonlinear effects, etc. Also, the amplitudes of loads and stresses at resonances and when passing through resonances are very difficult to predict and to assess their subsequent damage.

Experimental operational experience and theoretical analysis must proceed together hand-in-hand for designing future turbines. Large machines tend to use analysis more heavily than small machines, which often favor a build them and run them approach.

More simplified analyses, such as the whirl flutter analysis of a teetered rotor reported here, should be performed in order to understand the basic mechanisms involved. Longer, more complicated computer codes should only be done as a final verification of the system.

The "bins" format seems to be a good way of standardizing the performance evaluation of wind turbines.

The description of the many small wind turbine failures at Rocky Flats points to the need for more engineering rigor and better detail design for such machines.

The small turbine people are interested in quick and simple computer codes to help them design their turbines."

K. Hohenemser The following is from the Summarized Conclusions Section of his review.

"The application of available analytical methods cannot guarantee a correct prediction of structural dynamics properties of wind turbines. Many of the methods are too complex for application to the dynamic design anyway. The aerodynamic inputs are crude and oversimplified. The estimation of stiffness characteristics is difficult and may be erroneous. Particularly large errors must be expected in the prediction of resonance responses because of the uncertainties about aerodynamic and structural damping. Random inputs should be used where available. Random response analyses are the natural tools for determining the long term structural survival probablility. While the analytical tools for estimating linear aeroelastic stability margins are at hand, this is not the case for stall induced nonlinear phenomena like stop pounding of teetering rotors. Because of the unreliability of analytical predictions, funding of new wind turbine projects should include a generous portion for an extended period of development testing to correct possible errors in the structural dynamics design. The structural dynamics problems are relatively benign for HAWT's, particularly for upwind designs. These problems are more difficult for vertical axis machines with their strongly nonuniform blade loads aggravated by wake crossings."

R. Thresher

The following is an excerpt from the section Some Thought and Suggestions.

"The design considerations for the new "soft" systems which seem to be of concern to a large number of people are the following:

1. Dynamic loads and their computation for soft structures.
2. Static and dynamic stability of flexible turbines.
3. Control system interactions with the flexible structure.
4. Fatigue life and its computation.

These design considerations are directly related to the following basic technical issues of broader interest:

a. Yaw aerodynamics modeling and turbine forces.
b. Turbulence and the resulting aerodynamic forces.
c. Stall phenomena and the resulting aerodynamic forces.
d. Wake behavior and aerodynamic forces.
e. Damping in wind turbines and the resulting loads.

The design concerns and the technical issues are tied together in several ways, but the basic problems stem from a lack of understanding of fundamental physics as it applies to wind turbines. It may be that we can no longer just adapt helicopter technology to the needs of wind turbine development; we may need to formulate our own theories.

I see two related tasks for improving our dynamics analysis capability to reduce the risk associated with the development of an advanced generation of wind turbines. The first involves providing the necessary data with which to systematically revalidate the computer codes for the new soft configurations. This must be done in such a manner that the areas of strength and weakness in existing codes can be discovered. Then the second task will be to improve the predictive capability. The work should not only involve code validation, but must include validation of theory. This is the one area that has received little attention in the past, and is much more important for the advanced designs, because of our limited understanding of the basic physics."

W. Walton "NASA should expedite the development of the MOSTAS code to the point of validation and documentation or cancel the project."

The key points motivating this conclusion are expressed in the review as follows:

1. Very generally the companies with wind turbine development contracts have worked out their own methods and computer codes for structural dynamics analysis and they have done this in a timely manner.

2. All the companies have used the NASTRAN code for the supporting structural analysis and the results have checked well with structural tests.

3. Very generally the companies have utilized separate procedures for analysis of vibrations and dynamic stability.

4. In one instance a company tried the MOSTAS code and rejected it as unreliable.

5. In one instance a company used a code developed in-house at a government laboratory (NASA/Army Ames Research Center) for substantiation of dynamic stability.

6. In one instance a company used MOSTAB (a government supported code which is a predecessor to MOSTAS) as an aid for vibrations analysis.

7. In two instances companies have made direct use of personnel and methods from the helicopter industry for substantiation of dynamic stability.

8. None of the companies conveys any impression of inadequacy to deal with structural dynamics analysis nor do any of them seem to be seeking assistance.

# Review of 2nd DOE/NASA Wind Turbine Dynamics Workshop, Feb. 24-26, 1981

John Dugundji

The present memorandum gives a brief review of the 2nd DOE/NASA Wind Turbine Dynamics Workshop, together with some personal impressions of the general State-of-the-Art by the reviewer. The Wind Turbine Dynamics Workshop was held at Cleveland State University, Cleveland, Ohio on Feb. 24-26, 1981. The Workshop Chairman was Dr. David A. Spera of the NASA Lewis Research Center, while the Program Chairman was Prof. Robert W. Thresher of Oregon State University. About 175 persons were present.

## Purpose and Format of Workshop

In his opening remarks to the workshop, Dr. David A. Spera stated that the purpose of the workshop was to bring together technical people in the wind energy field and exchange information on wind turbine dynamic problems. From these discussion, it was hoped to be able to give answers to the following questions regarding the design of horizontal axis and vertical axis wind turbines:

1. Are the State-of-the-Art tools satisfactory?

2. Are the State-of-the-Art tools being used by industry?

3. What important verifications of theory are needed?

Professor Robert W. Thresher, in his opening remarks, discussed the organization and format of the workshop. There would be essentially four different session areas, namely, Aerodynamics, Structural Dynamics, Electrical & Control Systems, and Acoustics. These would be followed later by summary State-of-the-Art discussions. Papers presented at the workshop plus additional questions and answers would be subsequently published in a Workshop Proceedings, which would be available within a few months.

There were 52 papers presented at the workshop, of which about 45% were from industry, 25% from government, and 30% from universities. A copy of the actual program agenda is given at the end of this review. These papers provided a good glimpse of the current research problem areas and State-of-the-Art regarding wind turbines. A brief description of some highlights from various session areas follows.

## Aerodynamics

R. Wilson presented some analysis of the difficult wake interference problems associated with VAWT's. Also, he pointed out that for HAWT's, unconventional aerodynamic "vortex ring states" may exist in some off-design operation states which result in quite different performance than conventional momentum theory predictions. D, Jeng did some refined HAWT performance calculations using vortex theory with a rigid wake. T. Egolf also did such refined vortex theory calculations, and further noted that small errors in drag coefficient $C_D$ estimates may be more significant to performance calculations than vortex theory refinements. I. Paraschiviou and T. Base each presented papers on their analyses of the difficult load prediction and wake interference problems for VAWT's, while P. Klimas pointed out the need for better experimental performance data measurements on VAWT's, and proposed some experiments that will include both accelerationand pressure measurements. W. Wentz explored the possibility of utilizing more efficient laminar flow airfoil sections for wind turbines. However, he noted that keeping the blades surfaces clean during operation may offset the benefits from these airfoils.

R. Sundar explored the ramifications of HAWT performance in a turbulent atmosphere. He modeled wind gust spectra in 3-dimensions and considered the blade response as it sliced through the turbulence, thereby resulting in a mean and a fluctuating power coefficient. R. Thresher and W. Holley considered a similar problem but simplified the velocity fluctuations into an average fluctuation over the disk area plus first moments of the fluctuations in the horizontal and vertical directions. These first moment fluctuations were important in yaw and pitching responses of the rotor. H. Neustadter discussed experimental data analysis andpresentation of meaningful performance data on operating wind turbines using statistical sampling techniques. In particular, the use of the "bins" method was described. D. Spera discussed methods of verifying guaranteed minimum power levels for wind turbines, by introducing an analogy to conventional turbine-generator systems and by using the "bins" method of statistical sampling. C. Waldon gave an interesting slide presentation of various fatigue, gust, and overspeed failures of small wind turbines at Rocky Flats. He maintained many of these failures could have been prevented by more careful attention to detail design. W. Frost discussed the experimental measurement of wind turbulence levels, means and fluctuations, at various actual sites, and their agreement with analytical representations.

## Structural Dynamics

J. Dugundji reviewed analysis methods for rotating systems with periodic coefficients. This dealt with the use of Floquet methods and the use of multiblade coordinates and harmonic balance methods for investigating stability and forced response. G. Beaulieu discussed simplified methods of determining the natural modes and frequencies of twisted blades by using finite differences and the Myklestad method, rather than large finite element programs. D. Lobitz considered the natural modes and frequencies of VAWT's. It was found here that to match experimental resonances, the tower support motions had to be included, and this led to modification of conventional finite element analyses to include rotating coordinates. D. Janetzke presented a whirl flutter analysis of a teetered, elastic 2-bladed rotor on a pod free to yaw and pitch. The simplified analysis reproduced the basic features of a MOD-2 type structure and seemed to indicate it would be free of the basic flutter instability mechanisms. J. Hoffman discussed a hybrid analog-digital simulator that had been produced to solve given coupled rotor-tower equations of an HAWT. It could be useful for quick analyses of the effects of rotor design changes. Y. Yu addressed some simple analyses that were made to estimate loads and response of wind turbines in their early design stage. He pointed out significantly that most analyses cannot predict resonance amplitudes, since these are highly dependent on the level of structural damping assumed. Also, transient starting, stopping and gust loads are apt to be more severe than normal operating loads, and should be considered in analyses.

J. Glasgow reported on some carefully conducted experimental tests on the MOD-0 test vehicle. These related to comparisons of upwind and downwind operation with a teetered rotor. Yaw moments seemed somewhat greater upwind than downwind, while flatwise bending were predictably less. Equilibrium yaw angles of 50 degrees were found for free yaw tests. T. Sullivan reviewed resonance responses of the actual MOD-0 and MOD-1 turbines and indicated procedures to avoid potential resonances. Blade chordwise loads in connection with odd harmonic resonances of the drive train were noted as well as even harmonics associated with tower yaw frequencies. G. Bottrell described a passive cyclic pitch alternative to the teetering rotor to reduce blade moments. However, one must be careful of any soft torsional pitch spring to avoid a flutter condition. K. Hohenemser described some interesting experiments with a small 2-bladed HAWT with cyclic pitch variation and free to yaw. B. Broooks described some analyses that seemed to confirm roughly the MOD-0 free yaw behavior. Parametric variations on twist, coning, static balance and a delta 3 hinge were also performed to provide general trends.

## Acoustics

G. Greene discussed estimated versus measured wind turbine noise. For estimating noise, a combination of analytic methods and wind tunnel model tests are used and there is general agreement with measured noise. Upwind rotors were found to minimize noise. M. Snyder reviewed the general wake characteristics downstream of towers. N. Kelley gave a thorough investigation of the acoustic noise problem encountered by the MOD-1. He presented much on-site noise measurements and attempted to correlate pressure pulses and frequency spectra with complaints from residents. He felt much of the noise resulted from blade-tower interference effects, and could be minimized by decreasing rotation speeds from 35 to 23 RPM. R. Wells made a similar study of the MOD-1 noise and presented pertinent scaling principles for reducing the noise. W. Harris presented some analytical predictions of wind turbine noise using aerodynamic lifting line loads predictions together with acoustic theory. The reduction of the tower wake interference as well as reduction in rotation speed was suggested. F. Metzger presented some analytical and measured surveys of noise levels as well as people's reactions to it. He noted fewer complaints in towns where the background noise levels were higher. D. Thomson discussed refraction focussing of wind turbine noise by terrain, wind shear, and atmospheric conditions, and suggested that Boone, N.C. with its secluded valleys, may possibly have an exaggerated noise problem. L. Viterna described an analytic wind turbine sound prediction computer code developed at Lewis, while D. Stephens discussed methods for developing wind turbine acoustic standards. This latter attempted to set up noise criteria and test people to determine what levels were psychologically objectionable. These criteria bore some relation to those investigated a number of years ago in connection with aircraft sonic boom complaints.

## Electrical & Control Systems

The present reviewer did not attend these sessions, since he went to the simultaneously occurring acoustics sessions instead. However, from the program and subsequent state-of-the-art summaries, he surmised that research problem areas there dealt with the interaction of rotor-drive train torsional vibrations and power quality, effective power control systems, coupling of a wind turbine electrical output to a utility power grid, and interactions between an array of wind turbines attached to a utility power grid.

## Reports on MOD-1 and MOD-2

In addition to the formal papers, there were two informal progress reports on the MOD-1 and MOD-2 wind turbines.

D. Spera discussed the status of the MOD-1 turbine in Boone, N.C. The 200 ft. diameter MOD-1 turbine has accumulated over 300 hours operational time. There has been a noise problem, but they have achieved a 12 db reduction by operating at 23 RPM rather than the original 35 RPM. Unfortunately, on Jan. 20, 1981, there was a torsional failure of the drive shaft joint just behind the front hub bearing and all operations ceased until a repair can be made. The joint normally transferred torque by friction, but some preloaded bolts lost their preload and the joint failed. The cause of the failure is still being investigated. It was mentioned also that prior to failure, transient torsional loads about 80% higher than rated power loads were measured.

J. Andrews discussed the status of the MOD-2 turbine in Glendale, CA. The 300 ft. diameter turbine has accumulated over 56 hours operational time. Natural frequencies were tested on-site and seemed to agree within 3% of predicted values. The performance is being experimentally evaluated using the bins method described earlier. So far, the turbine seems to be operating satisfactorily, with no excessive teeter motion, excessive loads, or other problems. It was mentioned that the blade pitch control mechanism operates continuously as a rate damper between cut-in speed and rated power speed, to minimize oscillations. Above rated power speed, the pitch controller acts conventionally to dump excessive power. Movies were shown of the erection process at the site and they brought out impressively the large scale of the operations there. Two more MOD-2 turbines are being erected at the site and scheduled for completion by May 1981, so that the behavior of three large turbines and their electrical interactions can be observed.

State-of-the-Art Summaries

The session authors, chairman, and interested attendees gathered together after each session and discussed the state-of-the-art in their fields. The following are brief summaries of their discussions.

In aerodynamics, for HAWT's, the state-of-the-art tools seem satisfactory for performance analyses but not for dynamic loads and unsteady effects. Further work is needed on effects of dynamic stall, wake effects, yaw effects, and off-design operating regions such as the "vortex-ring state" at high tip speed ratios. Pressure measurement data also is needed in addition to the overall force and moments usually measured. For VAWT's, the aerodynamics are much cruder because of extensive wake interference effects, and more needs to be done. There seems also more need for atmospheric turbulence and gust environment statistical data. Manufacturers of large turbines use the state-of-the-art tools available, whereas manufacturers of small turbines would like simpler tools and codes. In fact, small turbine manufacturers are more apt to build them and run them based on limited analyses.

In Structural Dynamics, for HAWT's, the state-of-the-art tools seem satisfactory again for steady-state performance analyses, but not for transient and dynamic loads. The normal and the emergency shut down modes often give rise to the largest loads. Also, drive train braking gives severe loads and eats into fatigue life. Better descriptions of loadings over entire start-stop operation is required. In this connection, vibration resonances need to be avoided. Although their location in the frequency spectrum can often be identified, the actual amplitudes of the resonances and their subsequent damage is still not predictable, since this often depends on the structural damping and the nonlinearities present in the wind turbine. More work and data on these dynamic loads, fatigue life, and environmental effects is needed. For VAWT's, the state-of-the-art in structural dynamics is less well developed and needs more investigation. This is partly due to the fact that unlike HAWT's, there is no comparable helicopter technology to draw from. Manufacturers of large turbines use the state-of-the-art tools, while small turbine manufacturers tend not too. More communication between the two groups is desirable. For small manufacturers, survival wind loads tend to be a big designing factor, but they also have many fatigue and transient dynamic failures, as witness the test experiences of Rocky Flats. More engineering rigor and good detail design should be applied to these small turbine manufacturers.

In Acoustics, the state-of-the-art seems to be emerging satisfactorily. Although it is a relatively newproblem for wind turbines, it is based on older established investigations into propeller noise and sonic booms. Papers in the workshop dealt with various aspects of the problem such as experimental methods in wind tunnels, analytical predictions for wind turbine noise, gathering of on-site field data, and development of codes and criteria. The continuation of research into the above aspects of the problem should lead to satisfactory state-of-the-art tools. At present, only the MOD-1 has encountered a substantial acoustic problem, and this seems to be associated with tower wake interference effects and a sheltered, quiet environment area. Means of dealing with this and subsequent problems seems to be emerging.

In Electrical & Control Systems, the state-of-the-art tools appear satisfactory and at hand. Effort is being made to understand better the rotor-drive train-generator dynamic behavior and the resultant power oscillations in a given machine. Also, the electrical interaction of a machine with an electric power grid is being studied more. Since turbines often will be used as arrays in a wind farm, the electrical interaction between turbines in the array should also be considered. Both simple models as well as more complex ones can be used depending on the problem in hand. More experimental data on actual running wind turbines is needed, and that is now being accumulated.

## Personal Impressions

The reviewer's general impression of the 2nd DOE/NASA Wind Turbine Dynamics Workshop was that of an informative, generally high quality technical meeting, that brought people together to exchange ideas and that revealed the present state-of-the-art in wind turbine dynamics. The reviewer agrees with the state-of-the-art summaries presented by the various groups and described in the previous section. In addition, the reviewer would like to add some of his personal impressions of the general state-of-the-art, as follows:

The wind turbine field is moving ahead steadily, the body of knowledge is growing, and there is excitement as analysis, actual hardware, and operational experience develops.

Newer and more bold concepts are being tried, such as upwind rotors, free yaw machines, teetering blades, partial span controls, softer mounts, VAWT concepts, etc. More efficient wind turbines seem to be evolving from these concepts.

Wind turbine power performance predictions are sensitive to good estimates of drag coefficient $C_D$.

The "vortex-ring state" at high tip speed ratios should be better defined and recognized.

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For HAWT's, the free yaw behavior should be investigated further. The effects of coning angle, wind gusts, and yaw gusts should be better defined.

Knowledge of atmospheric turbulence is being gathered and applied to determine the power quality and fatigue response of the rotors. These involve random stochastic processes. Also required is a good discrete gust load criterion, based on statistical experience, comparable to the 1-cos gust used in the design of aircraft. Survival at hurrican wind loads seem to be reasonably defined.

Effects of transient loads such as gusts, emergency shut-downs, braking, on-off operation, etc. are still difficult to predict because of importance of damping, nonlinear effects, etc. Also, the amplitudes of loads and stresses at resonances and when passing through resonances are very difficult to predict and to assess their subsequent damage.

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More simplified analyses, such as the whirl flutter analysis of a teetered rotor reported here, should be performed in order to understand the basic mechanisms involved. Longer, more complicated computer codes should only be done as a final verification of the system.

The "bins" format seems to be a good way of standarizing the performance evaluation of wind turbines.

The description of the many small wind turbine failures at Rocky Flats points to the need for more engineering rigor and better detail design for such machines.

The small turbine people are interested in quick and simple computer codes to help them design their turbines.

The description of the MOD-1 failure seems to indicate that unexpected failures can also occur on large machines. Careful monitoring and inspection procedures should be incorporated, as well as the more extensive analysis and design procedures.

The erection of the MOD-2 seemed very impressive, and its operations so far seem good. It is to be noted that the system utilizes a continuously active pitch control system to provide damping in the range between cut-in speed and rated power speed.

The acoustic noise problem from turbines seems to be gathering understanding, and means for its control seems to be emerging. The importance of tower wake interference and quiet, sheltered environment is noted.

The dynamic behavior of the rotor-drive train-generator system seems an interesting new aerodynamic-structures-electrical power interaction problem which is being investigated analytically and experimentally. Interesting effects are beginning to emerge. The interaction of the wind turbine system with a loaded power grid, and with other machines in a wind farm array requires more analytic and experimental investigation. The state-of-the-art tools seem available for this, yet it will still be interesting to see what new effects and problems evolve when considering the entire system together.

**Thursday, February 26, 1981**
**Electrical & Control Systems (Dual Session)**
**Session Chairman - L.J. Gilbert (NASA LeRC)**

8:30 - "VAWT Drive Train Transient Dynamics"
D.B. Clauss (Sandia Labs.)
8:50 - "Dynamics & Stability of WTG's"
E.H. Hinrichsen & P.J. Nolan
(Power Tech., Inc.)
9:10 - "Kaman 40 kW WTG - Control System Dynamics"
R. Perley (Kaman Aerospace Corp.)
9:30 - "Automatic Control Algorithm Effects on Energy Production"
G. McNerney (U. of New Mexico)
10:10 - "Effect of Wind Power Changes on Utility System Dispatch"
R.A. Schlueter & G.L. Park
(Michigan State Univ.)
10:30 - "Problems Associated With Installation of a WTG on a Weak Feeder Line"
R. Goodrich (Northeast Util.Serv.Co.)
10:50 - COFFEE BREAK
11:10 - Author/Session Chairman Meetings
12:00 - LUNCHEON

**Acoustics (Dual Session)**
**Session Chairman J.P. Couch (NASA LeRC)**

8:30 - "Dynamics of Wakes Downstream of Wind Turbine Towers"
M.H. Snyder & W.H. Wentz, Jr.
(Wichita State Univ.)
8:50 - "Acoustic Noise Generation by the DOE/NASA MOD-1 Wind Turbine"
N.D. Kelley (SERI)
9:10 - "Refraction Focusing of Windmill-Produced Noise"
D.W. Thomson (Penn. State Univ.)
9:30 - "The NASA LeRC Wind Turbine Sound Prediction Code"
L.A. Viterna (NASA LeRC)
10:10 - "Wind Turbine Acoustic Standards"
D.G. Stephens (NASA LaRC)
1:30 - "Status of Downwind Rotor HAWT Noise Prediction"
F.B. Metzger & R.J. Klatte
(Hamilton Standard)
10:50 - COFFEE BREAK
11:10 - Author/Session Chairman Meetings
12:00 - LUNCHEON
1:30 - Session Chairman Reports
State-of-the-Art Discussions
3:30 - CONFERENCE CLOSE

Also, G. Greene "Calculated & Measured WTG Noise"
W. Harris "HAWT Noise"

R.W. THRESHER
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# SECOND DOE/NASA WIND TURBINE DYNAMICS WORKSHOP

February 24-26, 1981

University Center
Cleveland State University
East 22nd and Euclid Avenue
Cleveland, OH 44115

**Lodging**

Downtown Holiday Inn
2160 Euclid Avenue
Cleveland, OH 44115
(216) 696-5175

**Sponsors**

NASA Lewis Research Center
Cleveland State University
Oregon State University

**Workshop Chairman**

Dr. David A. Spera
NASA Lewis Research Center

**Program Chairman**

Prof. Robert W. Thresher
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**Arrangements Chairman and Host**

Prof. R. Kasuba
Dept. of Mechanical Engineering
Fenn College of Engineering
Cleveland, OH 44115
(216) 687-2575

** PLANNED AGENDA **

Monday, February 23, 1981

6:00-9:00 p.m. - Registration (Holiday Inn)

Tuesday, February 24, 1981

A.M.

7:30 - Registration (University Center)
8:15 - Introduction to the Workshop
D.A. Spera (NASA LeRC)
R. Kasuba (Cleveland State Univ.)

Aerodynamics I

Session Chairman - J.M. Savino (NASA LeRC)

8:30 - "Theoretical Aerodynamics of WTG's: A Review of Progress for Helicoidal Actuators"
L.W. Slager & D.E. Cromack (Univ. of Massachusetts)
8:50 - "Aerodynamic Potpourri"
R.E. Wilson (Oregon State Univ.)
9:10 - "Aerodynamic Performance Prediction of HAWT's"
D. Jeng, T. Keith, & A. Aliakbarkhanafjeh (U. of Toledo)
9:30 - "Double-Multiple Streamtube Model for Darrieus WT's"
I. Paraschivoiu (IREQ)
9:50 - "The UTRC WECS Performance Analysis for HAWT's"
T.A. Egolf (UTRC)
10:10 - COFFEE BREAK
10:40 - "The Velocity Field of a System of Unsteady Cycloidal Vorticies"
B.J. Young (Young Energy Systems)
11:00 - "Analytical Studies of New Airfoils for Wind Turbines"
W.H. Wentz (Wichita State Univ.)
J.T. Calhoun
D. Miller (NASA LeRC)
11:20 - "On the Wake of a Darrieus Turbine"
T.E. Base, P. Phillips, G. Robertson, & E.S. Nowak (Univ. of Western Ontario)
11:40 - "Recent Darrieus VAWT Aerodynamical Experiments at Sandia Labs."
P. C. Klimas (Sandia Labs.)
12:00 - LUNCHEON

Aerodynamics II

Session Chairman - J.C. Estes (NASA LeRC)

P.M.

1:30 - "Performance of WTG's in a Turbulent Atmosphere"
R.M. Sundar & J.P. Sullivan (Purdue Univ.)
1:50 - "Wind Response of HAWT's"
R.W. Thresher (Oregon State Univ.)
2:10 - "Wind Turbulence Inputs for HAWT's"
W.E. Holley (Oregon State Univ.)
2:30 - "Rotor Thrust-Loading Spectra for the 200 kW MOD-OA Wind Turbine"
H.E. Neustadter (NASA LeRC)
2:50 - "An Overview of Fatigue Failure at the Rocky Flats Wind System Test Ctr."
C.A. Waldon (Rocky Flats Plant)
3:10 - COFFEE BREAK
3:40 - "Performance Testing of a 50 KW VAWT in a Build-up Environment"
L.A. Schienbein (DAF INDAL Ltd.)
4:00 - "Calculation of Guaranteed Minimum Power Output for WTG's"
D.A. Spera (NASA LeRC)
4:20 - "The Hydraulic Windmill"
J.A. Browning (Browning Eng. Corp.)
4:40 - "The MSFC Wind Wheel Turbine"
W. Frost (FWG)
J. Kaufman (NASA MSFC)
5:00 - CLOSE

Wednesday, February 25, 1981

Structural Dynamics

Session Chairman - T.P. Cahill (NASA LeRC)

8:30 - "Review of Analysis Methods for Rotating Systems with Periodic Coefficients"
J. Dugundji & J. Wendell (MIT)
8:50 - "An Approximate Method for Solution to Variable Moment of Inertia Problem"
E.W. Deans (University of Toledo)
9:10 - "Computation of the Modes and Polar Moment of Inertia of the Blades of an HAWT"
D. Noisiux & G. Beaulieu (IREQ)
9:30 - "Dynamic Analysis of Darrieus VAWT Rotors"
D.W. Lobitz (Sandia Labs.)
9:50 - "Flutter of Darrieus Wind Turbine Blades: Correlation of Theory & Experiment"
N.D. Ham (MIT)
10:10 - COFFEE BREAK
10:40 - "Whirl Flutter Analysis of a Two-Bladed Teetered Rotor on an HAWT"
D.C. Janetzke & K.R.V. Kaza (NASA LeRC)
11:00 - "WEST Analyzers Using Hybrid Simulation Techniques"
J.A. Hoffman (Paragon Pacific, Inc.)
11:20 - "Dynamics of the MOD-6H Wind Turbine: Experience Based on the Use of MOSTAB-HFW Computer Code"
"Yi-Yuan Yu (Rockwell Intl.)
11:40 - "Comparison of Upwind & Downwind Rotor Operations of the DOE/NASA 100 kW MOD-O Wind Turbine"
J. Glasgow & D. Miller (NASA LeRC)
12:00 - LUNCHEON

Structural & Rotor Dynamics

Session Chairman - V.J. Weyers (NASA LeRC)

1:30 - "A Review of Resonance Response in Large HAWT's"
T.L. Sullivan (NASA LeRC)
1:50 - "SWECS Tower Dynamic Analysis Methods and Results"
A.D. Wright (Rocky Flats Plant)
2:10 - "Guy Cables Damping for VAWT's"
T.G. Carne (Sandia Labs.)
2:30 - "Free Yaw Wind Turbines"
G. Doman (Hamilton Standard)
2:50 - "North Wind 4 kW 'Passive' Control System Design"
H. Currin (Foehn Consulting)
3:10 - COFFEE BREAK
3:40 - "Passive Cyclic Pitch Control for HAWT's"
G.W. Bottrell (Ventus Energy Corp.)
4:00 - "Dynamics of an Experimental Two-Bladed HAWT with Blade Cyclic Pitch Variation"
K. Hohenemser & A. Swift (Washington State Univ.)
4:20 - "Mod-0 Dynamics Test Correlation"
B. Brooks (Hamilton Standard)
4:40 - "The Effect of $\delta_3$ on a Yawing HAWT Blade"
F. Perkins & R. Jones (Kaman Aerospace)
5:00 - ~~CLOSE~~ Status of MOD-1 & MOD-

# REVIEW OF STRUCTURAL DYNAMICS ANALYSIS METHODS FOR WIND TURBINES

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# Review of Structural Dynamics Analysis Methods for Wind Turbines

Kurt H.Hohenemser

## 1. Overview

The structure of a wind turbine generator is subject to atmospheric aerodynamic inputs and to control inputs. The structural deflections and their rates usually change the aerodynamic loads so that an aeroelastic treatment is necessary. Analytical input models assume either steady flow, transient flow for example from a discrete gust, or random flow. The structure reacts respectively with steady vibrations, with a transient response, or with random responses. For the structural dynamics analysis the structure must be given in terms of a stiffness and mass and damping distribution, whereby the stiffness values may depend on deflections leading to structural non-linearities. The solution of structural dynamics problems involves either stepwise integration of differential equations or finite element solutions as in the NASTRAN code and in others There are so called global codes like Rexor or C-81 and others which give a time history of the response, starting with certain initial conditions. Mild aeroelastic instabilities are difficult to recognize from such a time history. A modal analysis resulting in the various aeroelastic modes is preferable for stability analyses since even slowly growing dynmmic instabilities can be determined from the complex eigenvalues. The system must be linearized to perform a modal analysis. Such linearization from non-linear trim conditions is in many cases adequate. If non-linearities are essential as in stall induced instabilities a time history method must be used.

## 2. Aerodynamic Inputs

Aerodynamic inputs for working level methods are crude and inaccurate Usually a steady flow through the rotor disk is assumed with variations along the blade span determined by momentum or vortex wake considerations. The aerodynamic loads are obtained from two-dimensional airfoil data. Rather large errors can result from:

2.1 Three-dimensional Flow Effects. Near the blade root the boundary layer is thinned by centrifugal effects. Much higher lift coefficients are possible as compared to two-dimensional airfoil data. Near the blade tip a complex flow pattern involving the tip vortex can drastically change the airloads obtained with the working level analytical methods. The shape of the tip vortex and the resulting loads depend on the tip geometry.

2.2 <u>Dynamic Stall Effects</u> In gusts and in yawed flow certain blade sections experience transient stall. Little is known about the effects of a combination of transient stall and flow velocity changes. They are both ignored in working level methods.

2.3 <u>Inflow Distribution</u> The inflow distribution is usually only crudely assessed. It is strongly affected by the vortex wake pattern. Its proper computation is beyond working level methods. An erroneous inflow distribution can have a large effect on the in-plane aerodynamic damping which is needed for the assessment of in-plane blade resonances and of aeroelastic stability margins involving in-plane blade modes.

2.4 <u>Dynamic Inflow</u> In transient or random conditions the inflow pattern varies due to the dynamic interaction of the rotor with the surrounding air. This can have a large effect on control responses but is usually neglected.

2.5 <u>Random Flow Effects</u> Though not presently considered, random flow variations can have large effects on performance and on structural responses. Random flow models play a decisive role in airplane structural dynamics. Such models have so far not penetrated helicopter dynamic design procedures because pull-up maneuvers result in higher dynamic loads than atmospheric turbulence. For wind turbines the equivalent of a pull-up maneuver is steady operation in yawed conditions. Whether such a design condition can be sufficiently severe to yield higher dynamic loads than for a random flow analysis is not clear.

2.6 <u>Vortex State</u> Under certain conditions wind turbines may be operating in the socalled vortex state. There are no working level methods available to assess the aerodynamic inputs in this state.

In summary one can say that aerodynamic inputs from working level methods are not likely to result in correct predictions of structural responses or of aeroelastic stability margins. This fact is well recognized in helicopter technology where an extensive flight test program is needed for every prototype to uncover the usually large discrepancies between predicted and actual airloads. Often structural modifications result from the flight test program. In large wind turbines the situation may be somewhat better because of the preponderance of blade gravity loads and of storm survival loads which at least for some configurations may insure structural reliability in normal operation despite of the deficiencies in the analytical design methods.

## 3. Control Inputs

Controls are used to limit rotor torque, rotor speed and rotor thrust when operating above rated wind speed. Controls are also used to either avoid large yaw angles with their associated loss of power and increase in dynamic loads, or to limit torque and thrust by yawing the turbine out of the wind. Since control inputs are relatively slow the usual assumption of quasi-steady aerodynamics may be acceptable. The possibly large effects of dynamic inflow should be checked. The selection of the control system has a large influence on the dynamic loads. It was pointed out during the Workshop that the usual control feedback from the electrical generator output can cause substantial turbine and drive train loads if an electrical fault occurs in the grid. Normally the turbine is isolated from the electrical generator by a very soft interconnection which in itself will not react to electrical faults unless they are transmitted directly to the rotor by the control feedback system. The same soft interconnection makes it unlikely for the turbine to have a detrimental effect on the grid which can absorb without difficulties the power variations originating in the turbine. It appears that the complex control systems used to obtain an improvement in the so-called " quality of power " are unneccessary and even detrimental to the wind turbine dynamics. Below rated wind speed electrical power output will fluctuate widely with wind speed anyway. There appears to be no compelling reason why power should be held closely constant above rated wind speed by a sophisticated control system with detrimental effects on turbine responses to electrical faults. Synchronization shocks are easily avoided by adequate drive train flexibility. Thermal overloads of the generator are avoided if the mean power is equal to the rated power independent of power fluctuations about this mean. Obviously the turbine control system must be capable of preventing excessive transient torques close to the " collapse torque " of the generator.

In some recent designs wind following is accomplished by free yawing of a downwind turbine. There are many parameters affecting the free yawing characteristics like uptilt of rotor axis, coning angle, power output, yaw damper setting and others. A prediction of the free yawing characteristics requires a sophisticated analysis and its reliablity appears to be not good. If such a design is selected a subsequent test period with the potential of appropriate modifications must be planned.

For smaller wind turbines the complex blade feathering controls have occasionally been replaced by a simple furl control of a fixed pitch rotor. Because of a slower response of a furl control the power fluctuations above rated wind speed will be greater than for a well designed blade feathering control. In view of the much simpler fixed pitch rotor and in view of the greatly reduced storm loads on a rotor operating almost edgewise to the wind direction, it would be of interest to study the question whether a fixed pitch rotor with furl control has the potential of reducing the cost of energy also for large wind turbines. As compared to a Darius type of wind machine the structural dynamics and storm survival loads should be quite benign and the power excursions should be smaller. A fixed pitch furling rotor does not need hydraulic or electrical controls.

## 4. Structural Modeling

Structural modeling of the blade by either distributed stiffness and mass or by finite elements is usually not a problem. There are many non-linear terms which can be avoided if linear perturbations from a non-linear deformed state are considered. Despite much emphasis in the literature on the non-linearity of the structural description, the non-linear terms usually do not have a very large effect. Most errors arise not from neglected non-linearities but rather from erroneous evaluations of the stiffness characteristics of a composite and redundent structure. The same is true of the rotor support, nacelle and tower stiffness properties. Many free standing towers do not have a cantilever boundary condition at the foundation, its assumption can cause large errors in the predicted tower dynamics. Even with the more sophisticated methods used in helicopter structural dynamics it is rare that the dynamic characteristics can be properly predicted during the design phase. Modifications must then be made on the basis of ground and flight testing. Similar experiences have been made with wind turbines. One cannot expect that future designs will be much better unless they are very similar to preceding ones.

## 5 Analysis Methods

5.1 Modal Analysis. The simplest and most important method is a linear modal analysis resulting in the undamped modes and natural frequencies of the system. The analysis is first performed for one blade at rest and for the rotor support system. The effects of rotation and of coupling between blades and between rotor and support are then added. If the support stiffness is symmetrical one obtains in the rotating reference system even for a two bladed rotor a constant coefficient system of equations. Usually, the support is stiffer vertically than horizontally. In this case the two bladed rotor and support system cannot be described in terms of constant coefficients. Instead, a Floquet type of analysis with periodic coefficients must be used. This type of analysis has been described in many papers though it probably has not as yet penetrated the " working level " . The coupled modal analysis will show at what rotor speeds resonance free operation is possible and whether a mechanical type of instability exists. Later dynamic tests will usually show considerable deviations from the predictions.

### 5.2 Analysis of Forced Response

The forced responses outside resonances are reasonably well predictable. However, in the vicinity of resonances the response depends on the assumed aerodynamic and structural damping which are both difficult to estimate. Unless experience with similar geometries and structures are available, a prediction of a resonance response is unreliable. It can only be determined by tests.

### 5.3 Transient Analysis

Time histories are computed for a number of critical transients like a single gust or a sudden drop of the generator load. The accuracy of the response is not better than that of the aerodynamic assumptions or of the structural representation of the system.

The transients are selected such that an upper limit of rotor speed, thrust or torque can be expected.

## 5.4 Random Input Analysis

A random input analysis requires knowledge about the wind spectrum and about the dynamic properties of the structure. As mentioned before, it is used routinely in airplane structural dynamics. It has not been adopted as yet by the helicopter industry despite of many pertinent papers on the subject matter. It is felt that for wind turbines a random input analysis will be important in order to differentiate the dynamic loads for various sites and for various types and sizes of wind turbines. A fatigue analysis should be based on the probabilities of load occurances. In contrast to the case of the helicopter with its severe maneuver load criteria, it seems dubious whether for wind turbines a similar substitute case can be defined without leading to an unreasonable and costly over design. Only a random input analysis will bring out the large differences between smaller wind turbines which respond to an entirely different part of the wind spectrum as compared to large wind turbines which respond only to the very low frequencies in the wind spectrum. For this reason large wind turbines seem to require less sophistication in the structural dynamics analysis. A considerable part of the wind spectrum for the higher frequencies is absorbed by a large wind turbine without causing a noticeable response.

## 5.5 Aeroelastic Stability Analysis

Linear aeroelastic instabilities are relatively easy to predict. Bending-torsion flutter can occur for torsionally soft blades. The softness may originate in the control system, particularly if blade pitching moments are spring balanced for control purposes. A whirl instability can occur if the lowest tower or nacelle natural frequency can coincide with the frequency of turbine rotation. Two-bladed rotors are particularly vulnerable to whirl instability unless there is a large difference between the support stiffnesses in the plane of rotation. Such differences occur in free yawing turbines between the vertical and horizontal direction. Mechanical instability can occur as a consequence of coupling the in-plane blade modes and rotor support modes. Linear parametric excitation can be treated with a Floquet type of analysis.

While these types of aeroelastic instabilities are readily analysable, stall induced instabilities are not. Two bladed helicopters with teetering rotors have suffered from destructive stop pounding conditions induced by stall, and many fatal accidents have been caused by this phenomenon. Stop pounding was repeatedly observed for the MOD-0 machine in the configuration with teetering blades. It occurred during gusts and persisted even after passing of the gust. The stall limits in this configuration were reduced by operating at 33 RPM rather than at the normal 40 RPM. No reliabl analytical method to treat the stall induced stop pounding phenomenon exists. For turbines with teetering blades sufficient stall margins must be kept even in the presence of strong gusts. It may become necessary to elastically restrain the teetering motion as has been done for some small two bladed wind turbines and also for some helicopters. Analytical methods need to be developed to treat the stall induced stop pounding conditions.

## 6 Summary and Conclusions

The application of available analytical methods can not guarantee a correct prediction of structural dynamics properties of wind turbines. Many of the methods are too complex for application to the dynamic design anyway. The aerodynamic inputs are crude and oversimplified. The estimate of stiffness characteristics is difficult and may be erroneous. Particularly large errors must be expected in the prediction of resonance responses because of the uncertainties about aerodynamic and structural damping. Random inputs should be used where available. Random response analyses are the natural tools for determining the long term structural survival probablity. While the analytical tools for estimating linear aeroelastic stability margins are at hand, this is not the case for stall induced non-linear phenomena like stop pounding of teetering rotors. Because of the unreliability of analytical predictions, funding of new wind turbine projects should include a generous portion for an extended period of development testing to correct possible errors in the structural dynamics design The structural dynamics problems are relatively benign for horizontal axis wind turbines, particularly for upwind designs. These problems are more difficult for vertical axis machines with their strongly non-uniform blade loads aggravated by wake crossings.

# REVIEW OF DYNAMICS TOOLS FOR DESIGN OF LARGE WIND TURBINES

by

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for

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## BACKGROUND

The primary analysis tool used for the design of large wind systems is one of several computer codes especially developed for predicting dynamic behavior of wind turbines. Most of these codes have their analytical origins in the field of helicopter dynamics. The following is a list of some of the codes which have been used to design the current generation of wind turbines:

a. MOSTAB-HFW -- developed by Paragon Pacific, Inc., under NASA contract, used for rotor loads calculations employing a time domain analysis. The code is in the public domain.

b. MOSTAS -- developed by Paragon Pacific, Inc., under NASA contract for a complete multi-degree-of-freedom system analysis, which can provide solutions in either the time or frequency domain. This code is also in the public domain.

c. F-762 -- developed by Hamilton Standard for multi-degree-of-freedom time domain solutions of turbine dynamics problems. A proprietary code.

d. GETSS -- developed by General Electric Co. to perform multi-degree-of-freedom frequency domain analysis. A proprietary code.

e. REXOR-WT -- developed by Lockheed-California Co. for multi-degree-of-freedom dynamic analysis in the time domain. A proprietary code.

In addition to these computer codes, the designer and the analyst generally use a number of ad hoc codes to examine specific issues.

A question of major importance is the validity of the computer codes, and the accuracy of their predictions. The code validation efforts which have been on-going since the beginning of the wind program have generally shown reasonable accuracy. This capability has led to a general feeling of confidence in the industry, which has allowed designers to pursue a rapid design evolution in the space of only a few years. It is generally accepted that rapid design evolution is closely tied to the ability to forecast dynamic loads, and that reducing energy costs is in turn linked directly to continued design evolution. This is illustrated by the factor of two decreases in energy cost from the first generation Mod-1 wind turbine to the second generation Mod-2 turbine.

The first generation of wind turbines is considered to be a stiff design. They have truss towers with natural frequencies greater than twice the rotor angular speed. In addition, the rotor blades are rigidly cantilevered from the hub of the turbine main shaft, which is also structurally stiff. The "stiff design" is generally considered to be a conservation approach; however, this philosophy requires the use of more material and thus inevitably leads to higher costs. Both the Mod-0 and the Mod-1 are of this "stiff design".

The second generation of wind turbines, Mod-2, is more flexible. The tower natural frequency is between one and two times the rotor speed, and the tower is a cylindrical shell. Moreover, the rotor is not rigidly attached to the hub, but is attached through a teeter hinge to allow the rotor to flap in and out of the plane of rotation and relieve a substantial portion of the unbalanced aerodynamic loads. In addition, the Mod-2 incorporates a more flexible drive shaft to reduce the rotor torques in the drive train. These are the major design changes which led to the cost reductions over the first generation turbines. These changes resulted from the ability to compute dynamic loads for wind turbines of the "stiff design", and the associated design computations showing that it would be impossible to build a cost competitive machine using this approach. As a natural outcome, designers looked at the benefits of a more flexible turbine. The computer codes tended to confirm that the loads would in fact be much reduced with the more flexible machine, and the second generation Mod-2 was developed. However, it should be noted that the computer codes had not been validated for these flexible designs, so that the evolution toward a "soft design" involved significant risk. It seems doubtful that private companies would have taken this step without support.

With this background in mind, it is appropriate to attempt to look ahead to see what sort of improvements will be under consideration for the next generation of wind turbines. Then with the technology direction in mind, it is easier to examine the question of the readiness of the dynamics tools.

## THE NEXT GENERATION

Cost is still the key to wind turbine design, but as with the past generation of wind turbines, reduction of the dynamic loads is seen as the means to achieving the major cost reductions. Although there is not complete agreement on the configuration of the next generation, the following tabulation gives some of the features being considered:

Most Probable

a. Soft tower - to reduce cost and attempt to dynamically uncouple the tower from the rotor and nacelle. The tower natural frequency may be lower than 1/2 the rotor frequency.

b. Teetered hub - to reduce loads transferred to the tower and possibly to reduce yaw moments, or for yaw heading control in free yaw systems. Improvements depend on placing the teeter hinge at an angle, delta-3, to obtain cyclic pitch control with teetering.

c. Soft drive train - to uncouple the rotor from the gearbox and generator, and reduce loads, which will increase fatigue life and improve the turbine output power quality.

Possible

d. Free yaw - to improve heading control, reduce yaw loads, and increase energy capture over controlled yaw turbines. This has precedence since most small systems are free yaw; however, small systems seem to have a fairly high failure rate which has often been blamed on erratic yaw behavior.

| | | |
|---|---|---|
| e. Passive pitch control | - | to simplify the machines and eliminate a failure prone element. This includes fixed pitch rotors which seem to have appeal for reducing costs. This requires operating the rotor fully stalled. |
| f. Variable speed | - | to increase the energy capture and improve the turbine power output. |

From this list it is clear that the trend will be toward turbines of much greater flexibility, and a greater degree of control freedom.

In general, this increased flexibility and greater number of rigid body degrees of freedom greatly changes the analysis codes from the ones which were validated for the "stiff design" such as Mod-0 and Mod-1. For this reason, I would like to examine a validation case in more detail.

## A VALIDATION CASE

In order to be an effective design tool for the next generation of wind turbines the computer codes must be applicable to the configurations under study. The major problem with soft structures is that they move more than stiff ones and the effect of damping becomes important. Much smaller excitations can now have an effect because the greater flexibility allows the response to build near any resonance, depending on the amount of damping. In addition, there are many more resonances in the lower frequencies where the various excitations are stronger.

To get an idea about how well the computer codes can handle this problem, I have selected two figures from a code evaluation report (NASA TM-79101), which illustrate the problem. Figures 2 and 3 from this report are shown below:

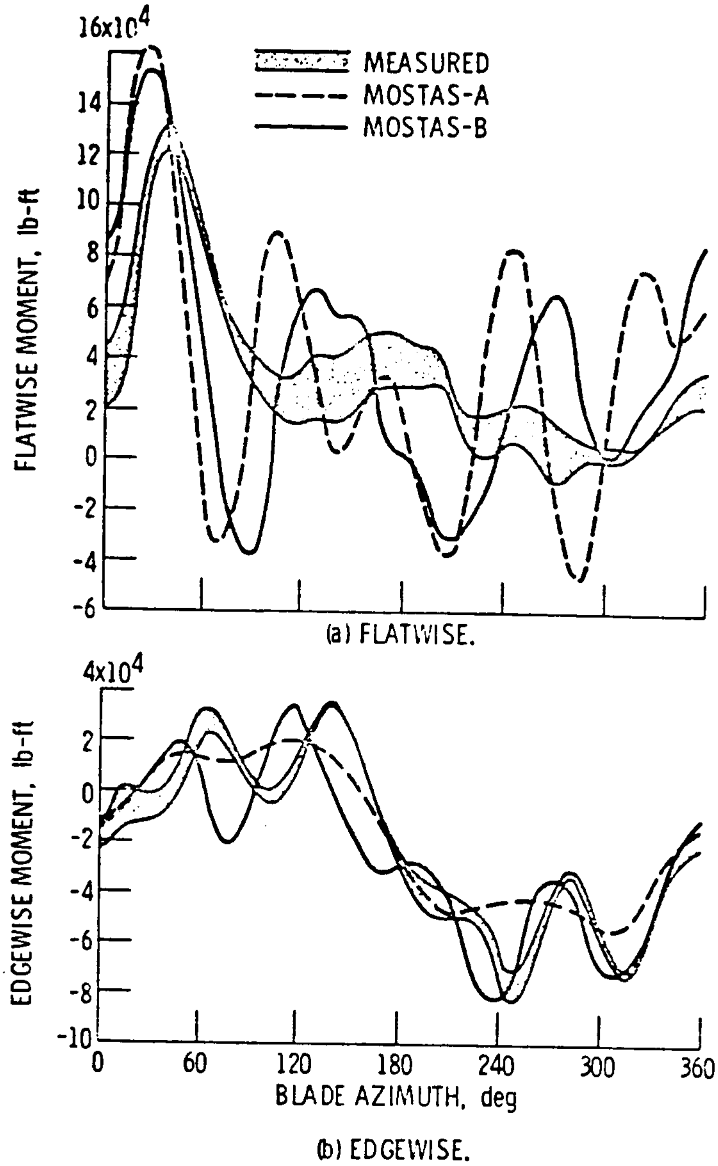


Figure 2. - Comparison of experimental and analytical bending moment time histories for single yaw case (at 5% blade span).

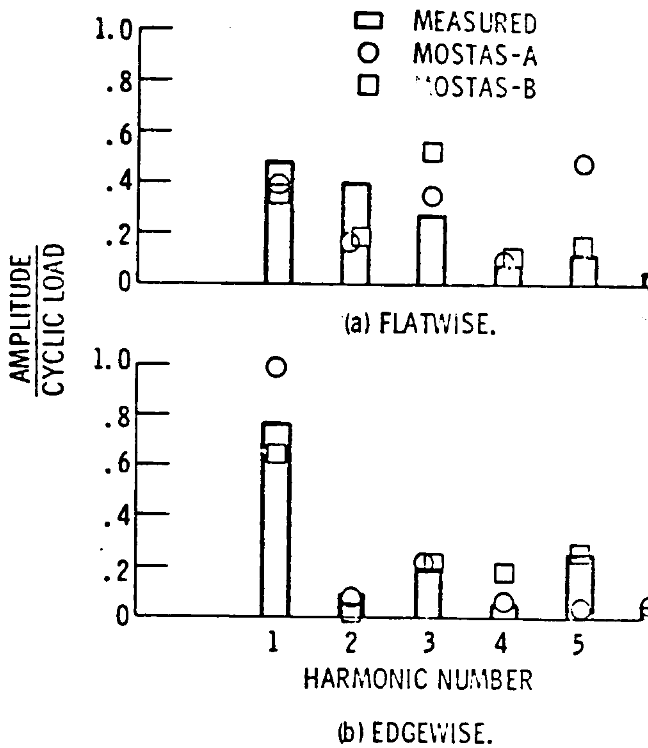


Figure 3. - Comparison of measured and calcu harmonic contents of moment load cycles.

The measured data in this case is for the original Mod-0 with stairs and a single yaw drive unit. As indicated in the report, this gave a pronounced response with large blade loads and significant side to side motion. This is just the sort of situation one would envision for a soft system operating near a resonance. However, this is probably a less difficult problem for the codes than a soft system with a teetering hub in free yaw. Examination of the above figures shows that the mean load and the overall cyclic load are predicted fairly well, but the fine structure is not very well described. At first this may not seem too important, but for the new soft systems it is important to be able to sort out whether cyclic response, such as shown in the flatwise moment, is due to some design feature, or an artifact of the computer code, as in this case. Furthermore, the codes will have a more difficult task predicting static and dynamic stability in the presence of rather uncertain aerodynamic forces, caused by the large structural motions of the more flexible systems. This sort of problem has already occurred with the F-762 code, which gave rather poor yaw trim predictions in the Hamilton-Standard wind tunnel tests.

In general, the yaw forces are the integrated effect of large cyclic forces, similar to those of Figure 2, and a small systematic error has a large influence on the yaw trim prediction, but a negligible effect on the blade bending moment. Finally, it is difficult to feel great confidence in our understanding of the dynamics of wind systems if Figure 3 represents our best effort. The fine detail is wrong, and thus the harmonic content is incorrect. I would conclude that the model is missing some important physical phenomena.

To conclude this particular discussion, it is my opinion that the computer codes are not ready to provide the sort of guidance which would be most helpful in sorting out the best features for an advanced "soft design" from the list of interesting possibilities described above. The codes have not really been validated for this sort of task, because there has not been an experimental machine of the proper configuration with which to pursue this validation.

SOME THOUGHTS AND SUGGESTIONS

The design considerations for the new "soft" systems which seem to be of concern to a large number of people are the following:

1. Dynamic loads and their computation for soft structures.
2. Static and dynamic stability of flexible turbines.
3. Control system interactions with the flexible structure.
4. Fatigue life and its computation.

These design considerations are directly related to the following basic technical issues of broader interest:

a. Yaw aerodynamics modeling and turbine forces.
b. Turbulence and the resulting aerodynamic forces.
c. Stall phenomena and the resulting aerodynamic forces.
d. Wake behavior and aerodynamic forces.
e. Damping in wind turbines and the resulting loads.

The design concerns and the technical issues are tied together in several ways, but the basic problems stem from a lack of understanding of fundamental physics as it applies to wind turbines. It may be that we can no longer just adapt helicopter technology to the needs of wind turbine development; we may need to formulate our own theories.

I see two related tasks for improving our dynamics analysis capability to reduce the risk associated with the development of an advanced generation of wind turbines. The first involves providing the necessary data with which to systematically revalidate the computer codes for the new soft configurations. This must be done in such a manner that the areas of strength and weakness in existing codes can be discovered. Then the second task will be to improve the predictive capability. One key bottleneck in this process will be the length of time required to change configurations on the Mod-0, which may require a second experimental turbine. Perhaps a smaller turbine of around 30 ft. in diameter would be adequate for some areas of work; it would be less expensive to modify and take far less lead time. The work should not only involve code validation, but must include validation of theory. This is the one area that has received little attention in the past, and is much more important for the advanced designs, because of our limited understanding of the basic physics.

Another area that I feel will become of increasing importance is the response of the more flexible designs to wind turbulence inputs. Much of the turbulence input can be thought of as a fluctuating component which is uniform across the rotor disk, but there is a second component which is just as important. The second component involves the turbulence gradient which makes the velocity different on opposite sides of the rotor disk, and can be thought of as a fluctuating wind shear that can occur at any orientation. Its mean value is zero, but at any instant it has some random magnitude and direction. This turbulence gradient causes teeter motions and yaw motions for free yaw machines. I think that the turbulence gradients may account for some of the observed cyclic responses that seemingly occur without a change in nacelle wind speed. Some of the necessary data to examine this type of response may already be recorded, but it probably is not in a very good format for this work. In addition, wind measurements that allowed computation of these turbulence gradients would improve the prospects of understanding the turbine responses, and probably improve code validation efforts.

In another wind related matter, it seems that the development of a set pf extreme load and wind statistics for the field test turbines would be most useful. I would suggest collecting the data in statistical form using the method of bins. For a given wind speed bin, the minimum data should include the mean loads and the variances, and some type of information on the extremes. I would accumulate this data in yearly periods, or in seasons. This would provide considerable insight for fatigue computations. I recognize that there are an infinite number of ways to present the data, but I am looking for a means to get the general picture without having to examine large amounts of data.

ONE POSSIBLE APPROACH

I suggest that the Wind Program should provide the basic data with which the technical community could validate their analysis codes for highly flexible turbine systems. This could be done in a number of different ways. Possibly by soliciting test programs to be run on the Mod-0 experimental turbines, or by jointly planning with the industry a set of experiments that would cover a range of important features. I favor a very basic set of initial experiments planned and executed by NASA Lewis Research Center, with guidance from the technical community. These first experiments would then be followed by a series of industry-requested test programs that would aid in the development of specific designs, or would help in understanding the fundamentals of wind turbine dynamics and aerodynamics. All data from these experiments would be in the public domain, but the specific use for any data could be totally up to the user. The criteria for accepting and scheduling test programs could be a problem, but as long as the experiments are fairly basic and the lead time is not too long the problems will be minimal. This type of program gives the initiative to the industry, but allows shared data for the benefit of the entire program. It starts out with the validation of the "soft systems" which I feel is of great importance at this time, and it provides for the validation of new theories and designs. In addition, it allows the opportunity to introduce cost sharing in the experimental program at some appropriate time.

Although it is clear that the turbine manufacturers prefer to develop and maintain their own dynamics codes, I think that is is important for NASA to maintain the development of some competitive dynamic analysis capability; however, this does not need to be a MOSTAS type of general purpose code. This NASA capability is required to run a safe and orderly test program. If NASA is to assist in the development of an advanced low cost wind turbine, the ability to analyze new innovative designs for dynamic capabilities is necessary. In addition, the wind turbine manufacturing field is new and companies may both enter and leave the field in the near future, so with one dynamics code in the public domain, the field is always open and less capability is lost should someone drop out.

DIRECT RESPONSE TO THE REVIEW QUESTIONS AND SUMMARY

1. The dynamic analysis codes have good predictive capability for the less flexible turbine designs, but I do not feel that they are satisfactory to support the design of a generation of highly flexible wind turbines. The computer codes have not been validated for the soft systems.

2. It is my opinion that the Large Wind Turbine technical community is making use of the available codes, generally their own. However, most of the design teams are not confident of their

codes for the new flexible turbines, although few would openly admit it.

3. I suggest that NASA should provide the data for a soft system valdation effort, and should move ahead to assist the industry with several combined theoretical and experimental studies to improve the dynamics predictive capability.

# AN ASSESSMENT OF STRUCTURAL DYNAMICS IN THE NASA-MANAGED PROJECTS TO DEVELOP WIND ENERGY TURBINES

by

William C. Walton, Jr.

CONTENTS

## INTRODUCTION

The Department of Energy (DOE) administers a broad program to harness the wind to produce energy. As part of the program the NASA Lewis Research Center (LeRC) has been managing development of a category of large wind turbine machines. Being rotary machines with large flexible rotors these wind turbines have some potential for problems of structural vibration and dynamic instability. This is an assessment of these two aspects of structural behavior based on a short investigation of the recent experience. The subject as a whole is referred to as "Structural Dynamics."

## CHARTER AND METHOD

The assessment was authorized by reference 1 wherein the Director of Energy requested a short review/assessment of structural dynamics technology in the wind turbine development program. Three objectives were ascertained from reference 2 wherein the Manager, Wind Energy Project Office gave guidelines: (1) Determine whether structural dynamics analysis tools are adequate to support design of the next large wind turbines, (2) Determine whether the tools are being satisfactorily utilized, and (3) At the reviewer's discretion, make any other comments on the whole field of wind turbine structural dynamics.

The method agreed on was that the reviewer should attend the Second DOE/NASA Wind Turbine Dynamics Workshop and base the assessment on what could be learned there, augmented if necessary by telephone interviews with LeRC and contractor personnel. It is understood that other reviewers of structural dynamics were assigned as well, but that there are no requirements for coordination or consensus.

## BASIS

During 1976-77 the reviewer served as Chairman of the NASA Ad Hoc Committee for the Review of Structural Dynamics for Wind Power Turbines. This was a deep review by a team with broad expertise, and the objectives were essentially the same as those of the current assessment. Reference 3 is the report of the committee, and of course this assessment relies on that report. In advance of the workshop the Wind Energy Project Office forwarded relevant reports issued since a compilation they made in 1976 (ref. 4). These reports have been taken into consideration.

As planned, the reviewer attended the workshop during February 24-26, 1981 and there received a great deal of information essential to the findings and determinations. The workshop sources are itemized as follows:

1. Reports by LeRC staff reflecting direct experiences with the DOE/NASA large wind turbine development programs and with test programs utilizing the wind turbine operated by NASA at Plum Brook Station.

2. Reports from the universities and industry on research and development of analysis methods applicable to wind turbine structural dynamics.

3. Briefing to the workshop participants by Boeing Company personnel on the status of the development of the Mod-2 wind turbine.

4. Briefing to the workshop participants by LeRC staff on the status of a current investigation of a failure involving separation of a coupling in the drive system of the Mod-1 wind turbine.

5. Planned open discussions by the workshop participants.

6. Private discussions with Boeing Company personnel about the Mod-2 development.

7. Extensive private discussions with personnel of the Hamilton Standard Company about the wind turbine development programs this company has undertaken.

8. Reports from the community interested in small wind turbines.

9. Private discussions with a manufacturer of small wind turbines.

The participants at the workshop represented well all technical viewpoints on wind power.

The workshop procedures allowed written questions to speakers with the speakers required to answer orally within time limits and required to provide written answers to all questions in the forthcoming proceedings. The reviewer systematically posed questions to the speakers about structural dynamics issues and in both open and private discussions systematically exposed personal perceptions about the issues. In this manner the subsequent assertions of this assessment were tested broadly against the reactions of the community. There was general concurrence.

In followup the reviewer conducted extensive telephone interviews with appropriate personnel at: (1) General Electric Company, (2) Hamilton Standard Company, (3) Boeing Company, (4) NASA Ames Research Center, (5) LeRC, and (6) DOE. The industry people seemed to be in all respects candid.

## FINDINGS

Perceived Status of Projects: Under DOE/NASA projects since the prior review (ref. 3), a number of large wind turbines have been placed in experimental operation, in public utility modes, at widely dispersed locations. The list of operational machines is:

| Designation | Number Operational | Rotor Diameter (ft.) | Designer |
|---|---|---|---|
| Mod-OA | 4 | 125 | NASA |
| Mod-1 | 1 | 200 | General Electric |
| Mod-2 | 1 | 300 | Boeing |

Two more Mod-2 machines are scheduled to be placed in experimental service shortly. Considerable operational experience has been built up for the relatively smaller Mod-OA machines. Operational experience with the relatively larger Mod-1 and Mod-2 machines is limited but is sufficient to establish structural dynamics behavior.

The Hamilton Standard Company is developing a machine (dia. 260 ft) evidently with commercial markets in prospect. The company is under contract to provide one of these machines to the Department of Interior (DOI) for service at Medicine Bow Wyoming. The Boeing Company and the General Electric Company are currently working under separate DOE/NASA contracts to design a category of machine designated the Mod-5. The object in these efforts is to bring to bear the best technology possible to drive down the cost of the energy produced. Rotor diameters for these machines could go to 400 ft. Negotiations are currently under way for a DOE/NASA contract with the Rockwell International Corporation to produce an improved machine with the smaller Mod-OA scale. This machine would be designated the Mod-6H.

Evolution of Designs: The Mod-OA and Mod-1 configurations conform to a baseline configuration which was much studied in the prior review. For the baseline machines two developments since the prior review should be noted: (1) On the Mod-OA machines the original blades which were of metallic, basically riveted aluminum, construction have been replaced by blades of laminated wood construction. (2) For both the Mod-OA and Mod-1 machines a yaw brake has been installed. This brake is fully applied when the nacelle is stationary and partially applied even when the nacelle is being traversed by the yaw drive system.

The Mod-2 machine incorporates the following changes: (1) Upwind operation, (2) Pitch control utilizing only an outboard portion of the blades, (3) No blade coning, (4) Teeter hub, and (5) Cylinder Tower. The nacelle yaw position is controlled (obviously necessary for upwind operation).

The Hamilton Standard machine may feature other differences including: (1) free yaw and (2) flexible tower. The free yaw concept eliminates requirements for yaw control mechanisms such as drive and brakes but necessitates downwind operation.

The Mod-5 and Mod-6H machines currently contemplated probably will not show configuration changes other than those which have been enumerated. Advanced materials and structures for the blades and advanced design of the power train may be expected.

Evolution of Design Approach: With regard to structural dynamics the baseline design approach has been to aim for a system which is stiff throughout with all resonance frequencies placed above the rated rotation frequency. To preclude amplification of inherent vibrations the designers have tried to avoid coincidence of resonance frequencies with integer multiples of the rated rotation frequency. For rotors with two blades, which all these machine utilize, it is considered particularly important to avoid resonances at the two per rev frequency. Generally speaking, rotating machines may exhibit several categories of dynamic instability. However, if all resonance frequencies are placed above the one per rev frequency as has been discussed most of the categories can be ruled out. The designers feel that it remains necessary to check for aeroelastic instabilities as part of the substantiation of a design.

Referring to he Mod-2 machine, Boeing's design approach for structural dynamics departs in only one respect from the baseline approach of a system which is stiff throughout. That is the introduction of a teeter hub. The designers adhere to the principle of placing all resonance frequencies above the one per rev frequency and also to the principle of avoiding coincidence of resonance frequencies with integer multiples of the rated rotation speed. It has been considered necessary to make analytical checks for aeroelastic instabilities. The teeter hub does not introduce possibilities for new categories of dynamic instability.

The Hamilton Standard machine apparently could depart in at least three ways from the baseline approach. There could be at least two articulations: (1) teeter hub and (2) free yaw, and (3) according to the flexible tower concept some resonance frequencies could be placed below the one per rev frequency. The last introduces the possibility of additional categories of dynamic instability. The types of dynamic instability which can be hypothesized are listed in reference 3. It is considered necessary to make analytical check for all these types of instability.

Influence of Vibrations: The prior review (ref. 3) identified a few categories of vibration determined to be of possible significance bearing on service life. The categories identified were all cyclic vibrations. No significant transient vibrations were noted. The possibly significant cyclic vibrations were determined to be predictable and to be in principle controllable within the baseline approach of a system which is stiff throughout.

At the time of the review there was a much discussed concern about amplification of inherent lateral vibrations due to resonance at the two per rev frequency. The factors controlling the relevant resonance behavior were identified to be tower bending stiffness and stiffness of the yaw controls. The Mod-1 designers were then inclined to the conservative approach of elevating these stiffnesses to place the resonance frequency above the two per rev frequency. It was recognized as a cost/risk issue whether the designers should use some other method to control this resonance. Noted alternatives included: (1) Tune the lateral resonance below two per rev and (2) Use a teeter hub to reduce requirements for stiffness of the yaw controls. As it has turned out the Mod-1 designers stuck with the conservative approach. Evidently the Mod-1 operational data now show that with this approach vibrations were quite adequately predicted and controlled, and no categories of vibration other than those identified by the review have been found. The approach led to two cost incurrences: (1) the yaw brake and (2) increased gages in the tower structure. A yaw brake was eventually installed on the Mod-OA machines after attempts to increase the yaw control stiffness by other methods.

The Mod-2 designers elected to tune the lateral resonance below the two per rev frequency (but above one per rev) and to use a teeter hub. However, the decision to go to the teeter hub was evidently motivated more by consideration of yaw control loads than by consideration of vibrations. Evidently except for the unavailable oscillating blade gravity loads, cyclic vibrations are altogther insignificant in this machine.

Influence of Dynamic Stability: For all the operational machines it appears that considerations of blade flutter could have been critical in sizing the blade pitch controls. It is difficult to be sure about this from a brief investigation because a number of factors influence the design of these mechanisms and the designers do not readily call to mind the interplay of factors. It is clear however that considerations of dynamic stability have influenced the design of no other mechanical components of the current machines.

As has been noted, the Hamilton Standard Company may elect to place resonances below the one per rev frequency introducing the possibility of additional categories of dynamic instability. This is recognized to make analysis checks for dynamic instabilities more demanding and critical. There are precedents for such analysis in the usual treatments of helicopter ground resonance and air resonance, and apparently Hamilton Standard is mounting an adequate analysis effort. The parent corporation, United Technologies, encompasses companies which design helicopters and aircraft propellers and also an industrial laboratory which normally deals with dynamics of rotary machines. Project personnel have been identified who are deeply experienced in both theoretical and practical aspects of the essential disciplines.

Analysis Methods for Vibrations and Stability: The prior review found that there is adequate basic knowledge for analysis of wind turbine structural dynamics and noted a tendency for developer companies to try to set up digital computer simulations of structural dynamics behavior accounting for all system interactions. Attention was called to NASA support of the development of a computer simulation, bearing the acronym MOSTAS, with projected capability to predict structural dynamics behavior and to predict loads and performance as well. The idea was that the code would be generally applicable and available to all. It was pointed out that all these computer simulations depend on supporting structural analysis and that adequate computer aids for this structural analysis, such as the NASA supported NASTRAN code, are widely available.

Relevant subsequent developments discovered by this investigation are:

1. Very generally the companies with wind turbine development contracts have worked out their own methods and computer codes for structural dynamics analysis and they have done this in a timely manner.

2. All the companies have used the NASTRAN code for the supporting structural analysis and the results have checked well with structural tests.

3. Very generally the companies have utilized separate procedures for analysis of vibrations and dynamic stability.

4. In one instance a company tried the MOSTAS code and rejected it as unreliable.

5. In one instance a company used a code developed inhouse at a government laboratory (NASA/Army Ames Research Center) for substantiation of dynamic stability.

6. In one instance a company used MOSTAB (a government supported code which is a predecessor to MOSTAS) as an aid for vibrations analysis.

7. In two instances companies have made direct use of personnel and methods from the helicopter industry for substantiation of dynamic stability.

8. None of the companies conveys any impression of inadequacy to deal with structural dynamics analysis nor do any of them seem to be seeking assistance.

Analysis Methods for Drive Train Dynamics: For wind turbines probably the most important outstanding design problem with a conceivable structural dynamics connection is the problem of achieving acceptable power quality. Here interactions between the electrical and mechanical systems come into play. The challenge is to design a power control system with sufficient stability and precision to meet public utility standards considering that the controlled element, the rotor, is very large and is flexible and that the flow of air from which the energy is derived varies randomly in speed and may be turbulent. For the most part this subject is behond the scope of this assessment. However, it is appropriate to ask if structural dynamics analysis tools are adequate for attacks on power control. It is very generally acknowledged that the answer is yes. It appears that in modeling the essential drive train dynamics the structural representation can be considerably simplified because the key frequencies are low, permitting if desired the assumption that the rotor is rigid. It follows that the structural components of the drive train can be represented by straightforward one-dimensional chains of torsion springs and rotary inertias. Such one-dimensional models are currently widely used for design studies of power dynamics. One company has checked the one-dimensional representation against a more comprehensive model accounting for blade elasticity. The conclusion is that the simpler structural representations in use are valid.

Comment on Structural Failures: There have been some in-service structural failures with conceivable implications that dynamic loads were missed or underestimated: (1) The original blade design for the Mod-OA machines showed a propensity to crack and for this reason has been replaced with another design (as noted). (2) Some Mod-1 tower bolts failed. (3) A bolted coupling in the Mod-1 power train failed. Also, external to the NASA managed projects, there have been numbers of failures of small commercially developed wind turbines at the Rocky Flats evaluation facility. There was much discussion of these small machine failures at the workshop.

Careful questioning of responsible personnel at LeRC indicates that both the original and the replacement Mod-OA blade structure designs have now been fatigue tested. The replacement blades survived fully simulated service loading whereas the original blades did not. In these tests the original blades evidently failed in the same manner as they did in the service failures. These facts are strongly indicative that the problem with the original blades lies with structural design and not with loads assessment.

The reviewer has some experience with investigation of bolt failures in rotary wing aircraft. It is really not possible to deduce much about the adequacy of design loads from bolt failures. The reasons are: (1) Bolt stress and the security of bolts depend on installation procedures and it is seldom that the rigor of such procedures can be established on a post-hoc basis. (2) With respect to the nominal design loads, bolted fixtures are usually so conservatively designed that failures cannot be logically related to the nominal loads.

Responsible personnel at LeRC, Boeing Company, and Hamilton Standard Company were interviewed very carefully as to how loads criteria have been derived and which categoreis of loads have been identified as critical for service life. The prior review (ref. 3) recommended that LeRC accord responsibility for developing loads criteria to industry. It appears that LeRC followed this recommendation by according full scope, with sufficient funding, to the Boeing Company to develop loads criteria as part of the Mod-2 development. It further appears that a careful job was done guided by good company and consultant expertise in wind statistics. The current developers are using essentially the same wind statistics as worked up by Boeing.

Loads which could ordinarily be termed "dynamic" have not emerged to be critical for structural design. The hurricane wind load is important. Significant repeated loads are: (1) Start-stop cycles and (2) (to a lesser degree) gusts. Yaw (torsion) loads on the tower may count among the repeated loads particularly for upwind operation. The only critical cyclic loads identified are the once per revolution gravity reversals on the blades which affect sizing of blade roots and hub. All of these loads can be calculated on an assumed-static basis.

The reviewer attributes the numerous failures of small commercial machines to the difficulty for small (often new) companies to muster the demanding loads assessment, resonance placement, and fatigue design efforts which are required and to which large aerospace companies are accustomed.

## DETERMINATIONS

1. Structural dynamics analysis tools are adequate to support design of the next large wind turbines.

2. The tools are being satisfactorily utilized.

3. NASA should expedite the development of the MOSTAS code to the point of validation and documentation or cancel the project.

## REFERENCES


1. NASA MEMO. 1/23/81, 4000 Director of Energy to 2000/Director of Structures: Review of Structural Dynamics Technology and its Application to Wind Development.

2. NASA Memo. 2/10/81, Ronald L. Thomas, Manager, Wind Energy Project Office to Reviewers at Second DOE/NASA Wind LTurbine Dynamics Workshop: Guidelines for Reviewers.

3. Report of the NASA Ad Hoc Committee for the Review of Structural Dynamics Technology for Wind Power Turbines.

4. NASA Memo. 2/9/81, Manager, Wind Energy Project Office: DOE/NASA Wind Turbine Dynamics Workshop



William C. Walton, Jr.
Leader, Rotorcraft Vibrations Group
NASA Langley Research Center

We agree with Hohenemser's conclusion in Section 5.1 that a constant-coefficient analysis is inadequate and that a Floquet analysis is needed. We have added Floquet analysis to MOSTAS, but this extension has not yet been validated.

Action Item No. 3: Validate Floquet analysis section in MOSTAS by June 1982 (D. C. Janetzke)

In Section 5.4, Hohenemser calls for a random wind input capability for loads analysis. Thresher also makes this recommendation. We have this capability in the WEST simulator, but it has not yet been validated.

Action Item No. 4: Validate random wind input capability of WEST simulator by June 1982 (T. R. Richards)

Field data on blade loads are still our first line of attack in establishing fatigue spectra. We now have a composite spectrum for rigid-hub rotors in excess of a half-million rotor revolutions. We believe this is adequate for design purposes. A similar data base will be constructed for teetered-hub rotors.

Hohenemser concludes that an analysis of teeter-stop pounding induced by blade stall is needed. We agree, but feel that the emphasis should be on testing of solutions rather than analysis of the problem. Recent private tests have shown that soft stops may be the solution. We will probably conduct similar tests at Plum Brook

Action Item No. 5: Provide analytical support as required for Mod-0 tests of soft teeter stops (L. A. Viterna)

In his summary, Hohenemser concludes that the state-of-the-art of analytical predictions is "unreliable" and therefore testing should be generously funded and extended in scope. We disagree with the use of the term "unreliable" to describe the state-of-the-art, but we do agree with the need for adequate testing.

## REVIEW BY ROBERT W. THRESHER

Thresher emphasizes the need for code validation for "soft systems" (i.e. teetered and/or with tower frequencies less than the rotor speed. We agree with his two recommended actions: (1) Provide data to validate codes (Our teetered-rotor code validation case V was provided to GE and BEC Mod-5 project teams) and (2) improve predictive capability (this will develop following (1)).

We disagree that advancements in theory are needed before structurally soft systems can be analyzed properly. Helicopter experience and our experience to date with wind turbines indicates that the state-of-the-art understanding of the "basic physics" is adequate.

# RESPONSE TO REVIEW REPORTS

D. A. Spera, D. C. Janetzke, and L. A. Viterna
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Cleveland, Ohio 44135

The conclusions and recommendations presented in the preceding state-of-the-art reviews were studied by the NASA Wind Turbine Analysis Section, for guidance in planning future research. Areas of agreement and disagreement were identified, clarifying notes were added, and action items were established. A summary of the NASA response to each review report follows.

## REVIEW BY JOHN DUGUNDJI

Dugundji believes more gust analysis is required. We agree. During the next year, Tim Richards, a member of the Analysis Section, will study wind gusts and the response of wind turbine structures to them, as a Ph.D. dissertation topic.

Action Item No. 1: Draft thesis on gust response of wind turbines by September, 1982 (T. R. Richards)

Further work on aerodynamics is recommended by Dugundji, as well as by two of the other three reviewers. We agree and are working on Mod-0 test plans and back-up analysis, particularly in the area of stall behavior.

Action Item No. 2: Plan aerodynamics research task by November 1981 (L. A. Viterna)

Dugundji believes more simple codes, each for a special-purpose dynamics analysis, should be developed. We agree. Our ASTER code was recently written to provide a simple model for aeroelastic stability analysis. We shall continue to supplement the MOSTAB/MOSTAS system codes, as recommended.

## REVIEW BY KURT H. HOHENEMSER

Hohenemser states that the frequency domain is preferable to the time domain for stability analysis, in digital simulation. We agree.

Improvements are required in aerodynamic analysis methods, particularly at the "working level" according to Hohenemser and several other reviewers. However, Hohenemser does not place much confidence in even the most complex aerodynamic theories. He prefers extensive testing, such as that done in the helicopter industry. We believe the term "crude" is a little harsh in Hohenemser's description of the accuracy of present aerodynamic analysis methods. We also disagree with "rather large errors". (See the Spera-Janetzke paper presented at the July DOE/NASA Workshop.)

Thresher recommends we (1) define turbulent wind loading conditions and (2) develop codes which can accept these conditions and give the system's response. We believe the WEST simulator can come closest to meeting these requirements. See Action Items No. 1 and No. 4.

The need for load statistics (spectra) was pointed out by Thresher. These spectra, for "stiff" systems were presented by Spera and Janetzke at the July DOE/NASA Workshop.

Experiments to validate predictions for soft systems cannot come earlier than tests conducted on the WTS-4 machine. These will meet Thresher's test recommendations. Testing of the WTS-4 might very well uncover new dynamics problems to be solved. This has already been our experience with Mod-0, -0A, and Mod-2. However, Hamilton Standard's F-762 code should be more than adequate to support the solution of any new dynamics problems with that machine. It is a time-domain code with close linkage to H.S.'s control system code. Our experience with Mod-2 suggests that new problems with the WTS-4 will include control-induced loads and transients. H.S. is equipped to analyze these types of problems.

We agree with Thresher that manufacturers prefer their own codes. Also, we agree that NASA should maintain an independent analysis capability (like MOSTAS and WEST). However, in most cases the MOSTAB-HFW rotor code will be adequate to check the manufacturer's analysis results.

## REVIEW BY WILLIAM C. WALTON, JR.

We agree with all three of Walton's determinations. The critical one is the third: Validate and document the MOSTAS code or cancel further work with it. We are now funding Paragon Pacific to do more validation and documentation of MOSTAS during the next 18 months. This is the only action recommended explicitly by Walton.

Action Item No. 6: Resolve MOSTAS validation questions and document by June 1982 (D. C. Janetzke/PPI)

Item 4 on page 8 is somewnat misleading. Boeing did try to use MOSTAB during the design phase of the Mod-2 system and did reject it, as Walton points out. However, BEC rejected MOSTAS because it was still having development problems and the project schedule did not allow the time needed to solve them. The code was not rejected for inaccuracy or deficiencies in modeling, nor was it rejected in favor of another system code, as might be implied by Item 4.

Whatever the reasons for not using MOSTAS to design the Mod-2, we are committed to making this code a useful analysis tool.

## CONCLUSIONS

The reviewers have provided valuable insights which the Wind Energy Projects Office will use to improve analysis tools and methods. Demonstrations of the MOSTAS computer code and the WEST simulator are the critical needs identified by the reviewers.